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Influence of mechanical surface treatments on fatigue strength of commercial purity titanium

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A comparative study of two mechanical surface treatments of shot peening (SP) and cold rolling (CR) on fatigue strength of commercial purity titanium has been conducted. The treated surface was characterized by using transmission electron microscopy (TEM), X-ray diffraction (XRD), and surface roughness measurements. Experimental result shows that SP and CR increased the fatigue strength of commercial purity titanium, and moreover, the following results were obtained: (1) The improvement of fatigue strength is related to the formation of deformation twins in strengthened layer. Before or after fatigue, the samples strengthened by SP or CR not only have twin shape and number change, but also have twin interactions in the SP and twin-grain boundary interactions in the CR. (2) XRD measurement demonstrated that SP leads to surface compressive residual stress are much higher than those after CR. Surface compressive residual stress has higher relaxation in the SP than in the CR condition during cyclic loading, then the surface compressive residual stress has the same values after fatigue deformation. (3) Surface roughness resulting from SP is ten times of CR. © *2003 Kluwer Academic Publishers*

1. Introduction

Titanium and its alloys have low density, high strength, high corrosion resistance and high chemical stability. These properties are very useful for many applications in various fields, such as biomedicine and in the aerospace and mechanical industries. However, the resistance against fatigue failure is the utmost importance in the safe design of engine structural parts and total joint replacements. Fatigue failure consists of two distinct processes: crack nucleation and crack propagation. Because the highest stresses occur on the surface of the specimen, cracks nearly always nucleate on the surface. Fracture occurs when the crack propagates to failure. Mechanical surface treatments have been widely applied to achieve the desired surface properties by the formation of a superficial hard layer. Mechanical surface treatments can be carried out by shot peening (SP) and cold rolling (CR). Several studies have been carried out in austenitic stainless steel and titanium alloys to increase the fatigue limit of cyclically loading mechanical components [1–4].

It is known that three factors, such as compressive residual stress, surface roughness and cold work, which are important in controlling fatigue behavior through effect on crack nucleation or crack propagation. Meanwhile, it is generally believed that the mechanism of specimen fatigue resistance is highly dependent on the mode of specimen; smooth specimens are mainly affected by cold work (microstructure) and surface roughness, but in notched specimen the effect are compressive residual stresses (stress).

In this paper we present the results obtained after mechanical surface treatment of commercial purity titanium by means of SP and CR. In an effort to determine the fatigue mechanisms, microstructures, compressive residual stress and surface roughness of the treated surfaces have been characterized and the fatigue strength has been measured.

2. Experimental procedure

The material studied in this investigation was commercial purity (CP) titanium obtained from the Northwest Institute for Nonferrous Metal Research of China. The chemical composition (wt%) was Fe-0.1; O_2-0.12; H_2-0.001; C-0.01; N_2-0.02; Si < 0.04. The fatigue specimens were of 20 mm width, 100 mm length, and 10 mm thickness. The SP and CR treatments were carried out on 10×100 mm^2 of specimens. The CP titanium was mechanically ground with sandpapers to serve as a reference. The specimens were shot peened at a pressure of 0.4 MPa using steel balls (0.2 mm diameter) and Almen intensity of 0.19 mm A. The cold rolling was conducted in a repeated contact fatigue machine.

The fatigue specimens were cyclically deformed in three point bending under stress ratio $R = 0.1$, in an

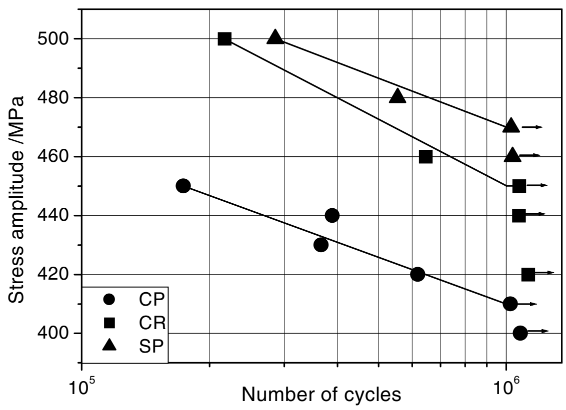

Figure 1 Effect of mechanical surface treatments (SP, CR) on S-N curves ($R = 0.1$).

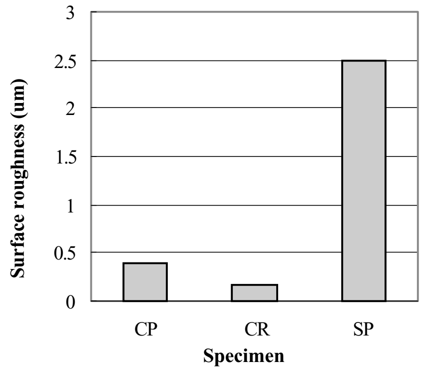

Figure 2 Comparison of the surface roughness among the CP titanium, CR, and SP. (Obtained from Surtronic3 profilometer).

Amsler-5100 high frequency machine at room temperature in air. Fig. 1 shows S-N curves after fatigue. Numerical value of 10^6-cycle fatigue life was defined as fatigue strength. The specimens fatigue strength for the CP, SP, and CR are 410 MPa, 470 MPa, and 450 MPa, respectively.

Residual stresses and transmission electron microscopy (TEM) investigations were carried out on the SP and CR states as well as on states fatigued up to 10^6-cycle numbers. Table I shows conditions on residual stress measurement. The residual stresses of SP and CR were obtained by computer-analysis. The subsurface residual stresses were obtained by using the so-called peeling method [5] (fatigued specimens were measured at peak tensile stress). TEM thin film samples were examined in a JEM-200CX machine.

3. Results and discussion

3.1. Surface roughness

Fig. 2 shows a comparison of the average surface roughness of CP, SP, and CR. Compared with the CP titanium, the surfaces become much rougher after SP. With the CR treatment, the surface roughness has been decreased to half the value of the CP surface.

A high surface roughness accelerates crack nucleation with no effect on crack propagation [2]. CP titanium is very sensitive to the surface conditions. High surface roughness can act as early microcrack nucleation sites, and reduce the fatigue strength.

TABLE I Residual stress measurement

Material	SP	CR
Instrument	D/Max-III X-ray diffractometer	MSF-2M X-ray stress analyzer
Ψ angle (deg.)	0, 20, 30, 40	0, 15, 30, 45
Peeling solution	10%HF + 5%HNO_3 + 85%H_2O	10%HF(42%) + 90%HCl(32%)
Stress constant (MPa)	261.7	
X-ray tube	Co K_α	
Diffraction plane	(222)	
Peak angle	$\sin^2 \Psi$-method (half width)	

3.2. Surface residual stress

The measured residual stress profiles are shown in Figs 3 and 4 for the CR and SP samples, respectively. SP leads to surface compressive residual stresses that are much higher than those after CR. Surface compressive residual stress gradually decreases with the depth from surface for the samples SP and CR. With cyclic loading, compressive residual stress profiles in both samples relaxed. However, the layer containing compressive residual stress extends to a depth of at least approximately 150 μm in SP as well as in CR.

For SP, a maximum surface compressive residual stress introduced is about −463 MPa. After cyclic loading, the surface compressive residual stresses reduced to −242 MPa. CR treatments lead to a maximum initial compressive residual stresses below the surface, are −219 MPa. When the CR samples were cyclic loaded, the compressive residual stresses change by a small amount compared to those of specimens before

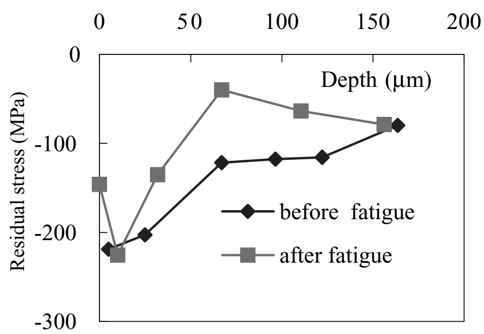

Figure 3 Residual stress distribution of CR sample.

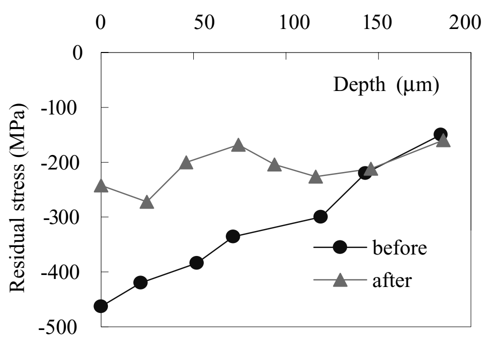

Figure 4 Residual stress distribution of SP sample.

fatigued. It is possible that the initial compressive residual stress values of CR are dependent on rolling force.Compressive residual stresses have little effect on crack nucleation, but can drastically retard crack propagation [1, 2, 4]. The relaxed compressive residual stresses mainly counteract the effect of applied tensile stress and can delay microcrack propagation in SP. The lower compressive residual stress has less effect on the crack propagation in CR, in comparison with SP. Fatigue behavior influenced by both surface roughness and compressive residual stress.

3.3. TEM microstructure

Further information about SP or CR microstructure leading to fatigue strength improvement can be obtained by TEM investigations. The microstructure of annealed CP titanium was equiaxed grains with an average grain size of 27 μm. There are a few dislocations inside the grains, but twins and stacking defaults are not observed, as shown in Fig. 5a. Dislocation density was extremely increased after fatiguing above 10^6 cycles (Fig. 5b), and even a few small deformation twins were also observed in the structure weakness of CP titanium, such as the site of tri-forked grain boundary [3].

It can be seen that SP as well as CR lead to a complex subsurface microstructure. By analogy with cyclic loading, CR treatment caused large numbers of dislocations in strengthened layer seen Fig. 6a. Moreover, deformation twin taper within a grain (Fig. 6b). Fig. 6c shows two twins intersecting at the given grain boundary, one twin ending at a grain boundary, a secondary twin is initiated on the opposite side of the grain boundary.

The SP treatment microstructure consists of deformation bands (Fig. 7a) of deformation twins with high dislocation densities (Fig. 7b) in the matrix. Deformation bands are parallel aligned; they can be explained with the reorientation bands (RBs) that consist of edge dislocations (RBs) [6]. The dislocation structures did not transform significantly when the SP samples were cycled over 10^6cycles, but the deformation twins increased in length and width, as a result of twin-twin interactions, which made it difficult to identify the original matrix (Fig. 7c).

From comparison of the CR and SP treatments on strengthened microstructures, it clearly can be seen that twin shape and twin number are changed and there are twin interactions in SP and twin-grain boundary interactions in CR. These phenomena correspond with the effect of strain and strain rate on deformation twins [7].

It is known that large strain, high strain rate and low temperature favor deformation twin initiation in pure titanium [6–9]. Since the number of slip systems of pure titanium is less than other metals with fcc or bcc lattice, twinning plays an important part in the plastic deformation to compensate for the limitation of insufficient slip systems. It is worth noting that the numbers of dislocation and deformation twins were very different in CR and SP. This phenomenon can be explained from the viewpoint of the deformation velocities quite different in CR and SP. In other words, due to the high strain rate in SP, dislocation density and twin density are enhanced. In addition, the dislocation and twin numbers decrease with increasing depth of the strengthened layer, because the deformation strain ranges vary with the distance from the surface.

Many investigations indicate that the crack nucleation sites were at the surface in SP and CR conditions. K. Takao and his coworker [10] have been studied the crack nucleation characteristics in pure titanium, and pointed out that microcracks nucleate along a grain boundary or slip band (related to the total strain range) and then the microcrack further propagates to form a main crack which becomes a starting point of final fracture. Meanwhile, slip-twin, twin-grain boundary and twin-twin interactions will cause a local stress concentration and can lead to secondary twin initiation or crack nucleation [8, 9]. In SP titanium, the coarsening and growth of deformation twins first induced secondary deformation twin initiation and propagation, then multiplication of twins with various orientation in a single grain may cause collision and interactions. Consequently, twin collision and interactions increased the probability of microcrack nucleation. While in CR titanium, twin-grain boundary interactions caused secondary twin initiation at opposite side of grain boundary, compare with crack nucleation. SP treatment therefore induces both microstructure strengthening and microstructure damage,

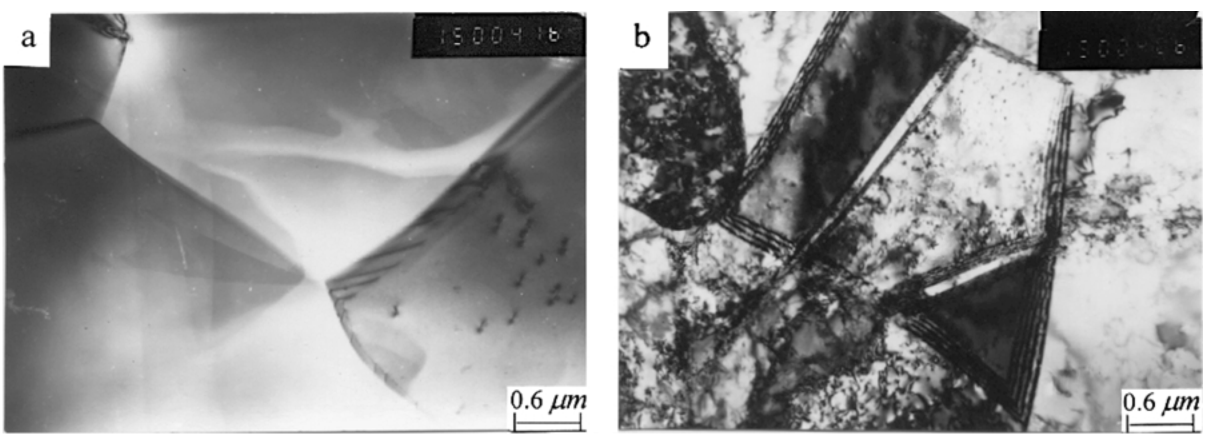

Figure 5 TEM micrographs of CP titanium specimens: (a) before fatigue deformation and (b) after 10^6 cycles.

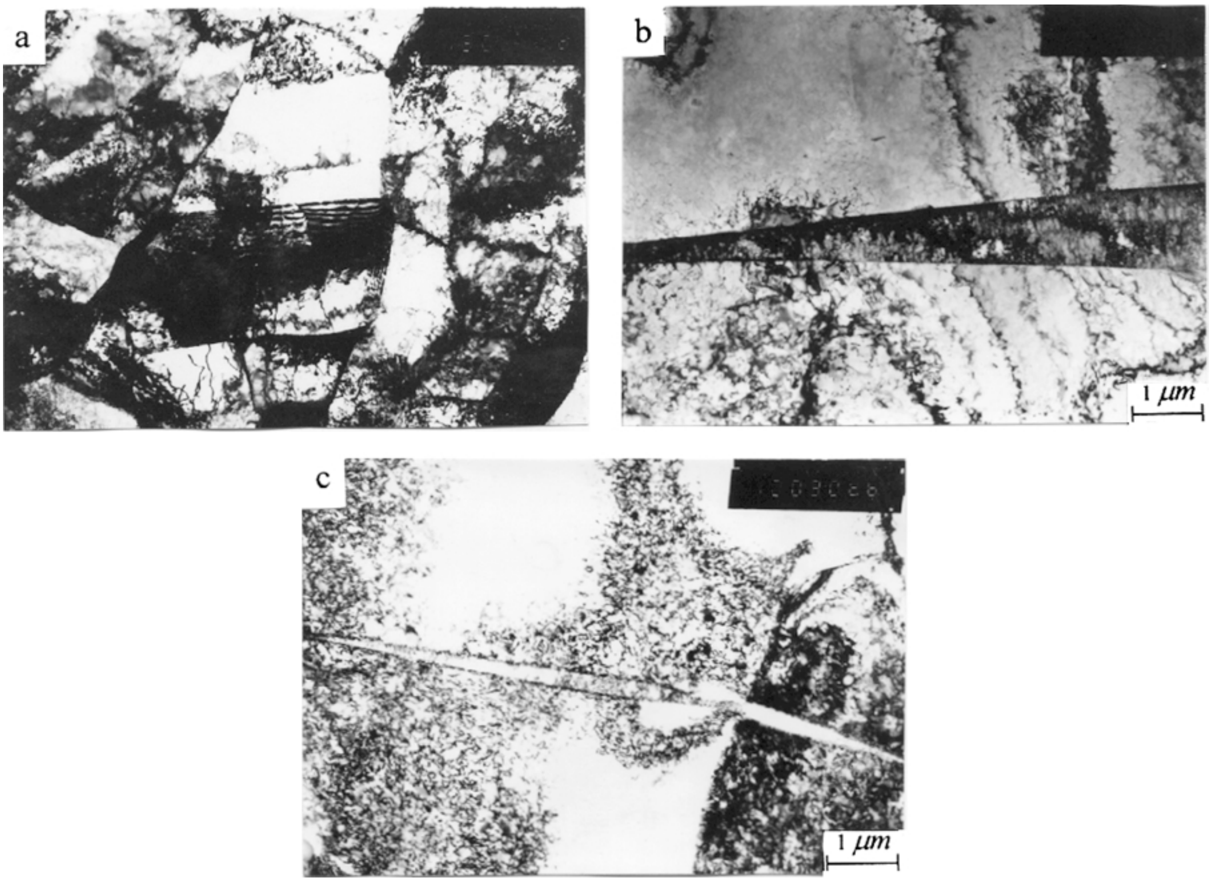

Figure 6 TEM micrographs of CR specimens (a) (b) before fatigue deformation and (c) after 10^6 cycles: (a) High dislocation density, (b) Deformation twin and dislocation, and (c) Twin-grain boundary interactions.

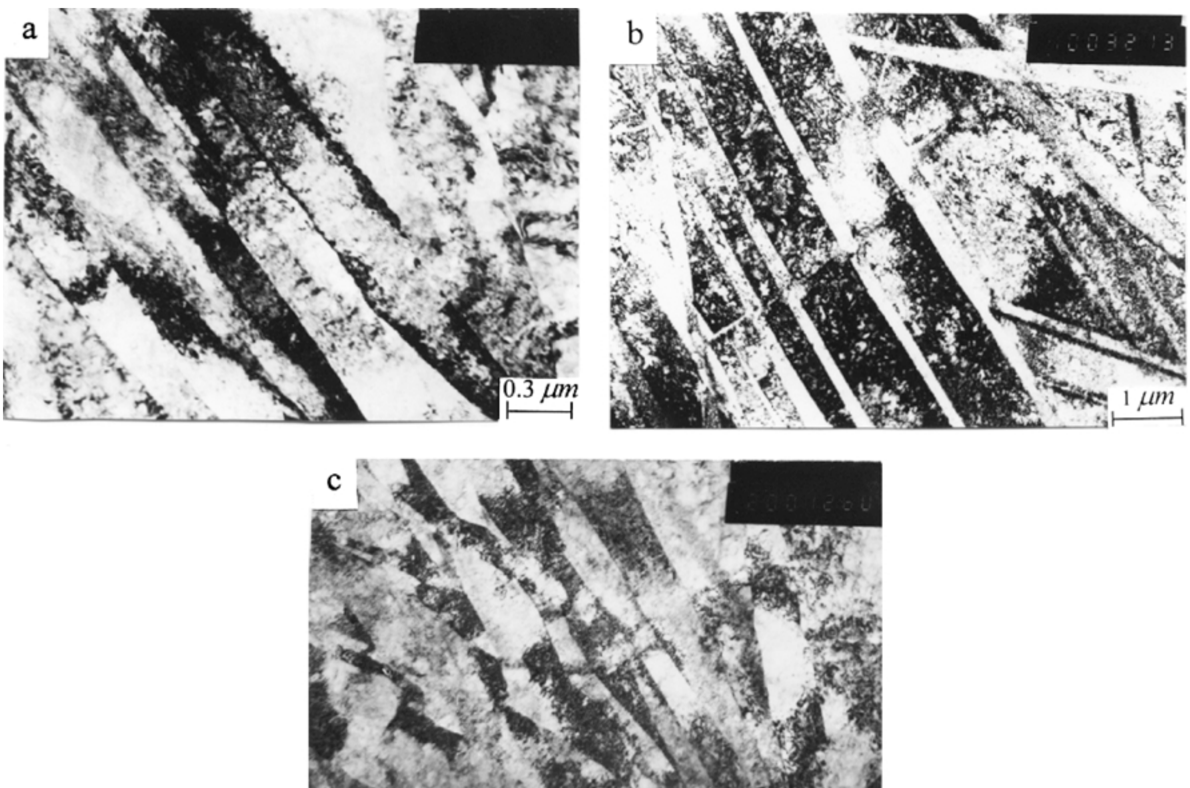

Figure 7 TEM micrographs of SP specimens (a) (b) before fatigue deformation and (c) after 10^6 cycles: (a) Deformation bands, (b) Deformation twins and twin interactions, and (c) Intensive twin interactions.

but CR treatment leads to microstructure strengthening alone.

Based on the observations, the fatigue strengths of the SP and the CR were improved because the deformation twins formed. However, the improvement of fatigue strength is disproportional with the number of deformation twins. The fatigue strength of the SP with high density of twins compared to that of CR with little twins was not enhanced significantly. This can be explained by the contradictorily factors in the SP. First, high surface roughness and twin interactions accelerate microcrack nucleation at specimens surface layer. Secondary, high compressive residual stress would retard microcrack propagation. Even though a microcrack may initiate in SP surface, it is difficult for it to propagate. Whereas in CR titanium, lower compressive residual stress can neither retarded cracks initiation nor significantly affected crack propagation. The improvement in fatigue strength of CR was primarily due to the formation of deformation twins.

4. Conclusions

(1) Compared with CP titanium, the fatigue strength of commercial purity titanium of SP and CR has been improved.

(2) Surface roughness resulting from SP is ten times of CR.

(3) X-ray measurement of the residual stress profile demonstrated that surface residual stress has higher relaxation in the SP than in the CR condition during fatigue deformation, but the surface compressive residual stress has the same values after fatigue deformation.

(4) The TEM revealed that dislocations and deformation twins are observed. Odd and dispersed twins are formed in the CR, but piles up twins and deformation bands are observed in the SP. After further cyclic deformations, twin-twin interactions in the SP and twin-grain boundary interactions in the CR play an important role, respectively.

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